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MASSES AND GRAVITIES OF BLUE HORIZONTAL BRANCH (BHB) STARS REVISITED

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ABSTRACT

Previous spectroscopic analyses of Blue Horizontal Branch (BHB) stars in six globular clusters revealed too low masses in four clusters when compared to canonical evolutionary theory, while the masses of the BHB stars in NGC 6752 and M 5 are found to be consistent with theory. We recalculated BHB star masses using new cluster distances derived by Reid (1997a,b) from HIPPARCOS parallaxes of local subdwarfs by main sequence fitting. The new distances are larger than previous estimates resulting in larger masses for the BHB stars. Since the increase in distance is small for NGC 6752 and M 5, the agreement with predicted masses persists. For M 15 and M 92 the masses now come into good agreement with theoretical predictions, while for NGC 288 and NGC 6397 the mass deficit is reduced but the BHB star masses remain slightly too low. Previous spectroscopic analyses also highlighted the problem of too low gravities for some BHB stars. The gravities and absolute magnitudes of BHB stars are revisited in the light of new evolutionary Horizontal Branch models.

Key words: Globular clusters; Blue Horizontal Branch stars; masses; gravities.

1. INTRODUCTION

Recent spectroscopic investigations of blue horizontal branch (BHB) stars in the globular clusters NGC 288, M 5, M 92, NGC 6397, NGC 6752 and M 15 (Crocker et al. 1988; Moehler et al. 1995, Moehler et al. 1997, and de Boer et al. 1995, hereafter CRO88 and papers I,III,II) showed that only in M 5 are the BHB stars an almost perfectly match the ZAHB prescription, both in gravity and in mass. The hottest HB stars ($T_{\rm eff} > 20000$ K and $\log g > 5.0$) are termed extreme HB stars or sdB stars since they spectroscopically resemble the sdB stars in the field very well (see Heber 1992). Besides M 5, NGC 6752 comes closest to the theoretical prediction at least for the hot end of the HB (sdB stars). Significant discrepancies between observational results and predictions by classical theory resulted for the other clusters and two main problems emerged:

1. The BHB stars (i.e. stars with 10,000 K $< T_{\rm eff} < 20000$ K and $\log g < 5$) showed **too low gravities** compared to standard evolutionary theory (CRO88, I). On the other hand cooler BHB stars as well as sdB stars were in good agreement with canonical tracks (II, III) in the ($T_{\rm eff}, \log g$) diagram. This is illustrated in Figure 4.

2. All BHB stars (except for M 5) had masses (on average) significantly below the canonical values of $0.5 - 0.6$ M$_\odot$(**too low masses**, I,II). The masses of the hottest HB stars (sdB stars) in NGC 6752, however, scatter around a mean value of 0.49 M$_\odot$, very close to what is expected from theory (0.5 M$_\odot$). (III).

The above mentioned papers also discussed a variety of possible explanations. The main problem turned out to be that it was not possible to find one solution that explained the too low gravities and masses at the same time, while keeping the "correct" masses and gravities of the sdB stars and the gravities of the cooler BHB stars.

Recently published HIPPARCOS results (Reid 1997a,b, Gratton et al. 1997) as well as new evolutionary tracks (Sweigart 1997) shed new light on these problems and offer solutions to the observed discrepancies.

2. HIPPARCOS PARALLAXES OF LOCAL SUBDWARFS AND THE DISTANCES TO GLOBULAR CLUSTERS

Reid (1997a,b) and Gratton et al. (1997) used HIPPARCOS parallaxes of nearby subdwarfs to redetermine the distances to a number of globular clusters, primarily using the abundance scales given by high resolution spectroscopy of cluster giants and field subdwarfs (Carretta & Gratton 1997, Gratton et al. 1997, Axer et al. 1989). Details of the fitting procedures can be found in the quoted papers. In Table 1 we give the new distances (together with the adopted reddenings and metallicities) for the globular clusters in question.

As can be seen from Table 1 the new distance moduli are always larger than the old ones, in some cases

Cluster	Djorgovski 1993			Reid (1997a,b)			Gratton et al. (1997)		
	[Fe/H]	$(m-M)_{V,0}$	E_{B-V}	[Fe/H]	$(m-M)_{V,0}$	E_{B-V}	[Fe/H]	$(m-M)_{V,0}$	E_{B-V}
NGC 288	−1.40	14.62	0.03	−1.07	15.00	0.01	−1.11	14.76	0.001
NGC 5904 (M 5)	−1.40	14.40	0.03	−1.10	14.53	0.02	−1.11	14.58	0.029
NGC 6341 (M 92)	−2.24	14.38	0.02	−2.24	14.93	0.02	−2.17	14.83	0.013
NGC 6397	−1.91	11.71[2]	0.18	−1.82	12.25	0.19			
NGC 6752	−1.54	13.12	0.04	−1.42	13.17	0.02	−1.40	13.20	0.028
NGC 7078 (M 15)	−2.17	15.11	0.05	−2.15	15.45	0.11			

[2] De Boer et al. (1995) used a distance modulus of 12.0 for their mass determinations

Table 1. The distances and reddenings derived from the new HIPPARCOS parallaxes compared to the old values.

by up to 0.55 mag (M 92). The effects are most pronounced for the metal poor clusters M 15, M 92 and NGC 6397, whereas the intermediate metallicity clusters NGC 6752 and M 5 are almost unchanged. The new distance for NGC 288 derived by Reid (1997b) is somewhat larger than that derived by Gratton et al. (1997).

3. MASSES OF BHB STARS REVISITED

Because the masses are derived from apparent magnitude, gravity and cluster distance, larger distances will result in larger masses for the stars observed in those clusters. In Figures 1–3 we plot the masses obtained with distance moduli listed by Djorgovski (1993) in comparison with the masses obtained from Reid's new distance moduli. Since the mass determination for an individual star has an uncertainty of at least ±0.2 dex, only the mass distributions are significant for such an comparison.

Figure 1 compares the masses of the BHB stars calculated from the new distance scale with those obtained from the old one for the clusters M 15, M 92 and NGC 6397, for which the new distances are substantially larger. As can be seen the new masses for BHB stars in M 92 and M 15 perfectly match the theoretical prescription. The scatter of the M 15 masses is considerably larger than for M 92 due to the lower accuracy of the gravities for the former cluster. Also the masses of the BHB stars in NGC 6397 are now closer to canonical predictions although there still remains a deficit.

Figure 2 plots the BHB and sdB star masses for NGC 6752 and M 5, the clusters with the smallest changes in distance moduli. Since the distance changes are small, the corresponding changes in masses are also small and the overall agreement of spectroscopically determined masses with the theoretical predictions remains very good.

Figure 3 plots the results for NGC 288. Since the new distance derived by Reid (1997b) is somewhat larger than the one derived by Gratton et al. (1997), we plotted masses calculated from both distance estimates in the bottom panel of Figure 3. As in the case of NGC 6397 the resulting masses are still too low when compared to the canonical values, even for the largest distance modulus of Reid (1997b), but the mass deficit is greatly reduced. Note in passing that the metallicity of NGC 288 rests on only two red giant stars, and therefore the determination of its distance might be affected via the selection of calibrating subdwarfs. VandenBerg et al. (1990) argue that the

colour-magnitude diagram, and therefore the abundance is very similar to that of M 5, which matches the Caretta & Gratton measurements.
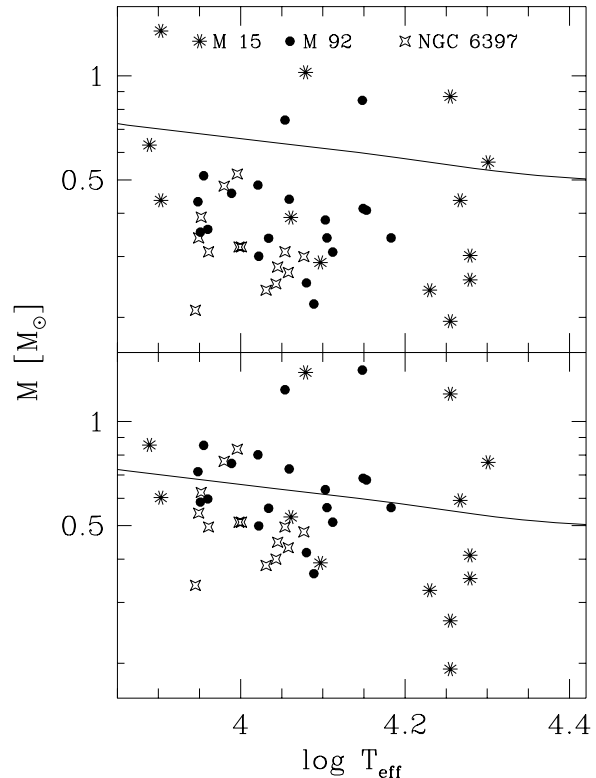

Figure 1. The masses of BHB and sdB stars in the metal poor globular clusters M15, NGC 6397 and M 92. The full drawn lines give the theoretical prediction from the models of Dorman et al. (1993, [Fe/H]=-2.26]) **Top:** The masses obtained with distance moduli as given by Djorgovski (1993). **Bottom:** masses obtained with the new distance moduli of Reid (1997a,b).

4. GRAVITIES OF BHB STARS REVISITED

As mentioned in the introduction not only the masses of the BHB stars posed a problem, but also their gravities. On average the gravities for stars with $T_{\rm eff}$ between 10000 K and 20000 K are too low, even when taking evolutionary effects into account. This problem is not affected at all by the distances of the objects so we have to look for another solution. Recently non-canonical models were calculated by Sweigart (1997) which take deep helium mixing
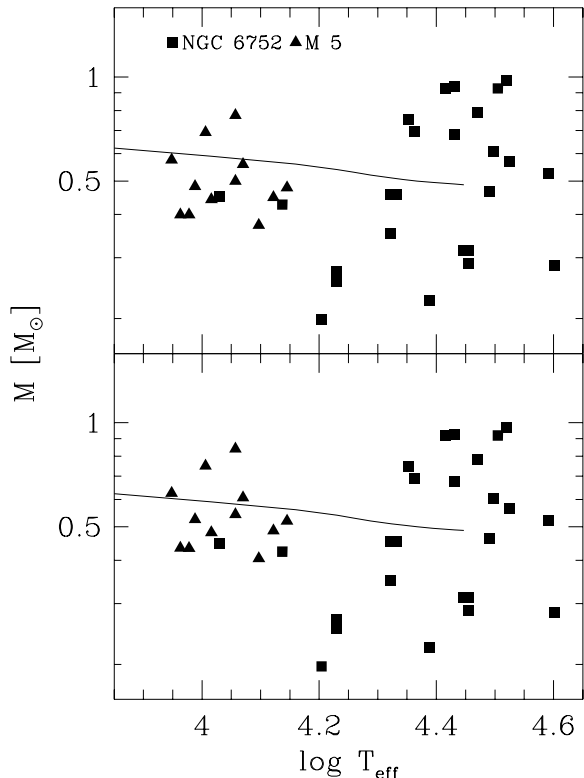
Figure 2. The masses of BHB stars in the intermediate metallicity globular clusters M 5 and NGC 6752. The full drawn line gives the theoretical prediction from the models of Dorman et al. (1993, [Fe/H=-1.48]). **Top:** The masses obtained with distance moduli as given by Djorgovski (1993). **Bottom:** masses obtained with the new distance moduli of Reid (1997b).
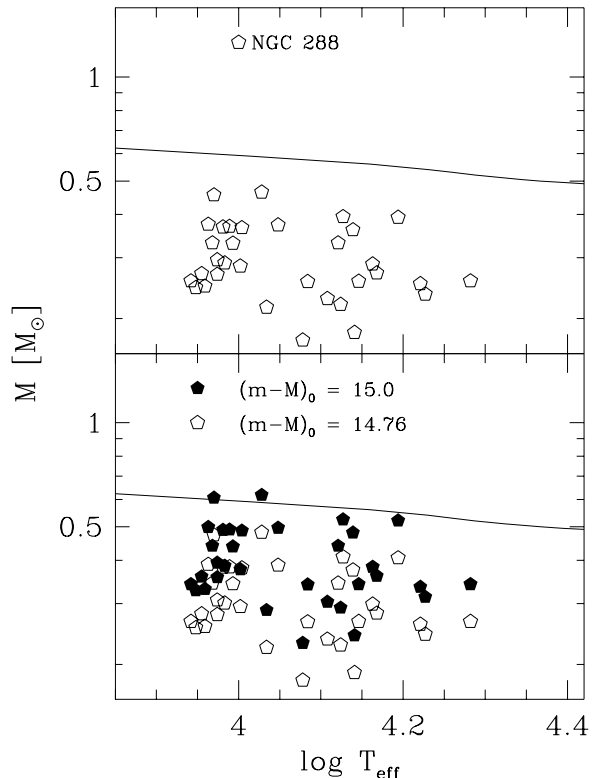
Figure 3. The masses of BHB stars in the metal poor globular clusters NGC 288. The full drawn lines give the theoretical prediction from the models of Dorman et al. (1993, [Fe/H=-1.48]). **Top:** The masses obtained with distance moduli as given by Djorgovski (1993) **Bottom:** masses obtained with the new distance moduli of Reid (1997b, full drawn) and Gratton et al. (1997, open symbols).

into account. In Figure 4 we compare the physical parameters of the cluster stars to these new tracks.

It is obvious from Figure 4 that deep helium mixing could explain the low gravities found for effective temperatures between 10000 K and 20000 K, while leaving the tracks for the sdB region virtually unchanged. However, there is no indication for helium mixing in the cooler BHB stars and it is not readily clear, why mixing should be important only at sufficiently high HB temperatures. On the other hand, stars with deep helium mixing tend to achieve bluer positions along the BHB, so there might be some correlation between the position on the BHB and the amount of helium mixing.

5. ABSOLUTE MAGNITUDES OF BHB STARS REVISITED

Increasing the distances to the globular clusters also increases the absolute visual magnitudes of the Horizontal Branch stars. In Figure 5 we compare the revised absolute magnitudes to the model predictions of Sweigart (1997). The theoretical HB band, defined by the zero age position (ZAHB) and the terminal age HB, is drawn from calculations without helium mixing and with a helium mixing parameter of $\Delta X_{\mathrm{mix}}=0.1$. The metallicity adopted in the

calculations is Z=0.0005 apropriate for NGC 6752, but slightly too large for the low metallicity clusters and too low for M 5 and NGC 288. Note, however, that the metallicity dependence of the BHB is very small (Dorman et al. 1993). The top panel displays the metal poor clusters NGC 6397, M 15 and M 92. The observed visual magnitudes are brighter than the theoretical ZAHB without mixing. The ZAHB for $\Delta X_{\mathrm{mix}}=0.1$ gives a resonable representation. The bottom panel of Figure 5 displays the more metal rich stars. For M 5 and NGC 288 the observed positions at the cool end (T_{eff}=10000 K) are well reproduced while the slope of the HB at hotter temperatures is shallower than predicted. This could possibly be explained if some helium mixing occurs at $T_{\mathrm{eff}} > 14000$ K. The sdBs in NGC 6752 are well reproduced by the canonical HB models. Note that the three stars lie above the HB have been identified as evolved post-HB stars (Moehler et al. 1997).

6. CONCLUSSIONS

We have redetermined masses and absolute visual magnitudes of BHB stars in six globular clusters using new (larger) cluster distances derived by Reid (1997a,b) from HIPPARCOS parallaxes of local subdwarfs by main sequence fitting. The masses for the BHB stars are larger than previous estimates. At
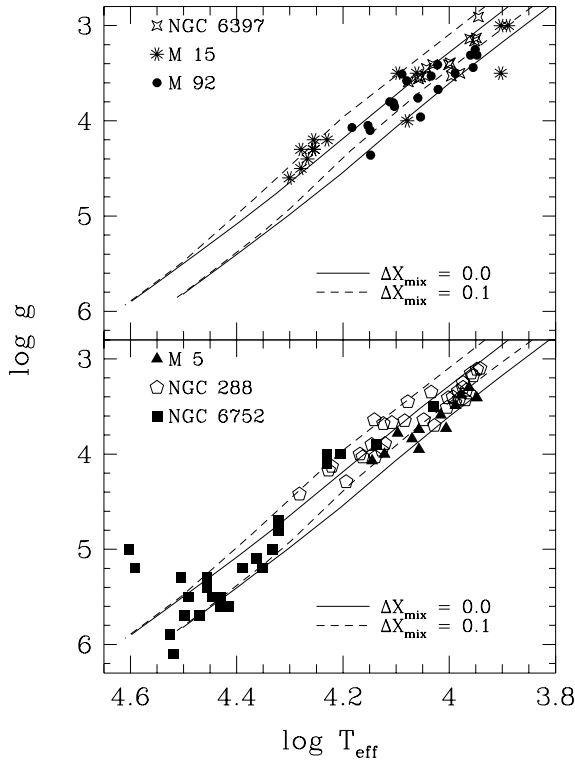
Figure 4. Gravities of BHB stars are compared to the location of the HB band from the calculation of Sweigart (1997) without helium mixing (full drawn lines) and adopting a helium mixing parameter of ΔX_{mix}=0.1 (dashed lines). **Top:** Comparison for the metal-poor clusters NGC 6397, M 15 and M 92. **Bottom:** Same, but for the intermediate metallicity clusters M 5, NGC 288 and NGC 6752.

Figure 5. Absolute magnitudes of BHB stars calculated from the new distances of Reid (1997a,b) are compared to the location of the HB band from the calculation of Sweigart (1997) without helium mixing (full drawn lines) and adopting a helium mixing parameter of ΔX_{mix}=0.1 (dashed lines). **Top:** Comparison for the metal-poor clusters NGC 6397, M 15 and M 92. **Bottom:** Same, but for the intermediate metallicity clusters M 5, NGC 288 and NGC 6752.

the new distance scale the masses for NGC 6752, M 5, M 15 and M 92 are consistent with model predictions of canonical evolutionary models. For NGC 288 and NGC 6397 the BHB star masses are still slightly too low but the mass deficit is reduced. The absolute visual magnitudes of BHB stars are consistent with those predicted by canonical theory for the cool end of the more metal rich clusters M 5 and NGC 288 as well as for the sdBs in NGC 6752 whereas the hotter BHB stars in these cluster as well as all BHB stars in the metal poor clusters are brighter than predicted by canonical ZAHB models.

In summary, the new distances to six globular cluster remove the problem of too low masses in two cases and weaken it in two other cases. However, at the same time they create a new problem for the BHB absolute magnitudes being too bright (at least for the metal poor clusters). If the new distance scale proves to be correct, the canonical evolutionary models underestimate the BHB brightnesses. This conclusion is corroborated by the too low gravities found for some parts of the BHB. Hence, we considered non-canonical tracks (Sweigart 1997) which included helium mixing and resulted in brighter BHB stars with lower gravities. While these models can reproduce the BHB magnitudes and gravities, further research is required to clarify whether deep He mixing occurs and which parameters determine the amount of mixing.
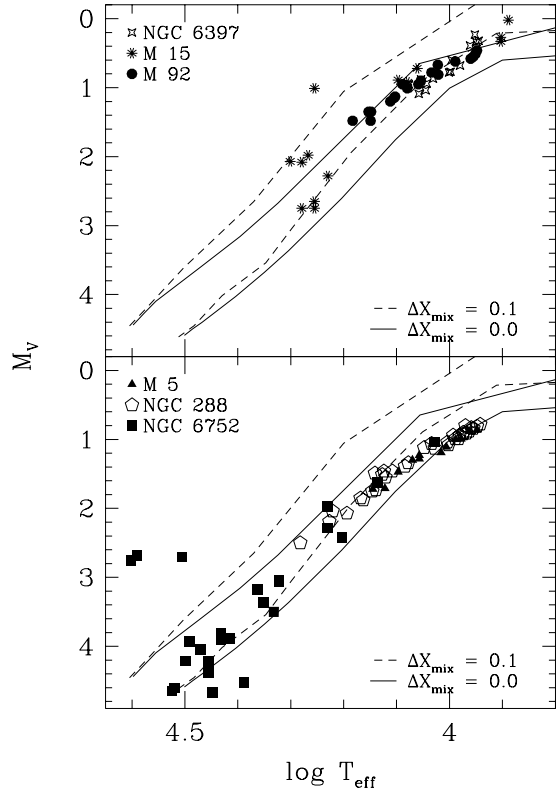
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